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Ultracold gas of excitons in traps

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6. AUTHORS
L.V. Butov

5d. PROJECT NUMBER

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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The Regents of the Univ. of Calif., U.C. San Diego
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14. ABSTRACT
We studied indirect excitons in coupled quantum wells. The main results are:

1. We discovered condensation and spontaneous coherence of excitons in a trap [Nano Lett. 12, 2605 (2012)].

2. We discovered patterns of spontaneous coherence, spin textures, and phase singularities in a cold exciton gas

15. SUBJECT TERMS
excitons, traps, condensation, coherence

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Leonid Butov
UU	UU	UU	UU		19b. TELEPHONE NUMBER 858-822-0362

Report Title

Ultracold gas of excitons in traps

ABSTRACT

We studied indirect excitons in coupled quantum wells. The main results are:

1. We discovered condensation and spontaneous coherence of excitons in a trap [Nano Lett. 12, 2605 (2012)].

2. We discovered patterns of spontaneous coherence, spin textures, and phase singularities in a cold exciton gas [Nature 483, 584 92012)].

3. We developed methods to trap cold excitons [Nano Lett. 9, 2094 (2009); Phys. Rev. Lett. 103, 087403 (2009); Appl. Phys. Lett. 97, 201106 (2010)].

4. We developed excitonic conveyer [Phys. Rev. Lett. 106, 196806 (2011)]. It realizes controlled transport of excitons as CCD realize controlled transport of electrons.

5. We developed excitonic devices operating at 100 K [Nature Photonics 3, 577 (2009)]. This is a two orders of magnitude increase in the operation temperature of excitonic devices compared to the previous record.

6. We measured kinetics of the inner ring in the exciton pattern formation and determined exciton transport characteristics [Phys. Rev. B 80, 155331 (2009)].

7. We measured the exciton front propagation in photoexcited GaAs quantum wells by time resolved imaging. These measurements afford a contactless method for probing the electron and hole transport [Phys. Rev. B 81, 115320 (2010)].

8. We demonstrated experimental proof of principle for all-optical excitonic transistors [Opt. Lett. 35, 1587 (2010)].

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/06/08 1	19	A. A. High,, A. K. Thomas,, G. Grosso,, M. Remeika,, A. T. Hammack,, A. D. Meyertholen,, M. M. Fogler,, L.V. Butov,, M. Hanson,, A. C. Gossard. Trapping Indirect Excitons in a GaAs Quantum-Well Structurewith a Diamond-Shaped Electrostatic Trap, Physical Review Letters, (08 2009): 87403. doi:
2012/06/08 1	18	A. A. High, A. T. Hammack, L. V. Butov, L. Mouchliadis, A. L. Ivanov, M. Hanson, A. C. Gossard. Indirect Excitons in Elevated Traps, Nano Letters, (05 2009): 2094. doi:
2012/06/08 1	17	A. T. Hammack, L. V. Butov, J. Wilkes, L. Mouchliadis, E. A. Muljarov, A. L. Ivanov, A. C. Gossard. Kinetics of the inner ring in the exciton emission pattern in coupled GaAs quantum wells, Physical Review B, (10 2009): 155331. doi:
2012/06/08 1	16	Sen Yang, , L. V. Butov, , L. S. Levitov, , B. D. Simons,, A. C. Gossard. Exciton front propagation in photoexcited GaAs quantum wells, Physical Review B, (03 2010): 115320. doi:
2012/06/08 1	15	Y. Y. Kuznetsova,, A. A. High, , L. V. Butov. Control of excitons by laterally modulated electrode density, Appl. Phys. Lett., (11 2010): 201106. doi:
2012/06/08 1	14	Y. Y. Kuznetsova,, M. Remeika,, A. A. High,, A. T. Hammack,, L. V. Butov,, M. Hanson,, A. C. Gossard. All-optical excitonic transistor, Appl. Phys. Lett., (05 2010): 1587. doi:
2012/06/08 1	13	A. Winbow, J. Leonard, M. Remeika, Y. Kuznetsova, A. High, A. Hammack, L. Butov, J. Wilkes, A. Guenther, A. Ivanov, M. Hanson, A. Gossard. Electrostatic Conveyer for Excitons, Physical Review Letters, (05 2011): 196806. doi: 10.1103/PhysRevLett.106.196806
2012/06/07 1	11	J. R. Leonard, A. T. Hammack, M. M. Fogler, L. V. Butov, A. V. Kavokin, K. L. Campman, A. A. High, A. C. Gossard. Spontaneous coherence in a cold exciton gas, Nature, (03 2012): 584. doi: 10.1038/nature10903
2012/06/07 1	10	A. A. High, J. R. Leonard, M. Remeika, L. V. Butov, M. Hanson, A. C. Gossard. Condensation of Excitons in a Trap, Nano Letters, (05 2012): 2605. doi: 10.1021/nl300983n
2010/03/25 1	9	S. Yang, L. Butov, L. Levitov, B. Simons, A. Gossard. Exciton front propagation in photoexcited GaAs quantum wells, Physical Review B, ( ): . doi:
2010/03/25 1	8	G. Grosso, J. Graves, A. Hammack, A. High, L. Butov, M. Hanson, A. Gossard. Excitonic switches operating at around 100 K, Nature Photonics, ( ): . doi:
2010/03/25 1	7	A. Hammack, L. Butov. Kinetics of the inner ring in the exciton emission pattern in coupled GaAs quantum wells, Physical Review B, ( ): . doi:
2010/03/25 1	6	A. High, A. Thomas, G. Grosso, M. Remeika, A. Hammack, A. Meyertholen, M. Fogler, L. Butov, M. Hanson, A. Gossard. Trapping Indirect Excitons in a GaAs Quantum-Well Structure with a Diamond-Shaped Electrostatic Trap, Physical Review Letters, ( ): . doi:
2010/03/25 1	5	A. High, A. Hammack, L. Butov, L. Mouchliadis, A. Ivanov, M. Hanson, A. Gossard. Indirect Excitons in Elevated Traps, Nano Letters, ( ): . doi:
2010/03/25 1	4	M. Fogler, S. Yang, A. Hammack, L. Butov, A. Gossard. Effect of spatial resolution on the estimates of the coherence length of excitons in quantum wells, Physical Review, ( ): . doi:
2010/03/25 1	3	A. Winbow, L. Butov, A. Gossard. Photon storage with subnanosecond readout rise time in coupled quantum wells, Journal of Applied Physics, ( ): . doi:
2010/03/25 1	2	A. High, E. Novitskaya, L. Butov, M. Hanson, A. Gossard. Control of Exciton Fluxes in an Excitonic Integrated Circuit, Science, ( ): . doi:
2009/10/22 0	1	G. Grosso, J. Graves, A. Hammack, A. High, L. Butov, M. Hanson, A. Gossard. Excitonic switches operating at around 100K, Nature Photonics, (09 2009): . doi:

TOTAL: 18

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
2012/06/08 14: 12	L.V. Butov, A.V. Kavokin. The behaviour of exciton–polaritons, Nature Photonics, (01 2012): 2. doi:

TOTAL: 1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Talks of Leonid Butov at conferences (since the start of the project in July 2008)

1.10. (plenary) Spontaneous coherence and condensation of excitons, The 42nd Winter Colloquium on the Physics of Quantum Electronics PQE-2012, Snowbird, Utah (Jan 2–6, 2012).

1.9. (invited) Indirect excitons: from the physics of cold gases to devices and back, 1st meeting of ITN INDEX, Modena, Italy (Dec 5–6, 2011).

1.8. (invited) Spontatneous Coherence and Spin Texture in a Cold Exciton Gas, Solid-State Lighting Science Workshop, Albuquerque, NM (Sep 14, 2011).

1.7. (plenary) Spin Texture in a Cold Exciton Gas, The 41st Winter Colloquium on the Physics of Quantum Electronics PQE-2011, Snowbird, Utah (Jan 2–6, 2011).

1.6. (plenary) Indirect Excitons: From the Physics of Cold Gases to Devices and Back, The 4th International Conference "Frontiers of Nonlinear Physics", Nizhny Novgorod – St.-Petersburg, Russia (Jul 13–20, 2010).

1.5. (invited) Transport and spin transport of excitons, The 11th International conference PLMCN “Physics of Light-Matter Coupling in Nanostructures”, Cuernavaca, Mexico (Apr 12–16, 2010).

1.4. (plenary) Exciton condensates, The 40th Winter Colloquium on the Physics of Quantum Electronics PQE-2010, Snowbird, Utah (Jan 3–7, 2010).

1.3. (invited) Indirect excitons in coupled quantum wells, The 9th International Conference Physics of Light Matter Coupling in Nanostructures (PLCMN9), Lecce, Italy (Apr 16–20, 2009).

1.2. (plenary) Indirect excitons, The 39th Winter Colloquium on the Physics of Quantum Electronics PQE-2009, Snowbird, Utah (Jan 4–8, 2009).

1.1. (invited) Cold exciton gases in coupled quantum wells, The 4th International Conference on Spontaneous Coherence in Excitonic Systems, Cambridge, UK (Sep 8–12, 2008).

2. Lectures of Leonid Butov at Summer Schools (since the start of the project in July 2008, these talks are not included to the Number of Papers presented but not Published).

2.3. Spontaneous Coherence and Spin Texture in a Cold Exciton Gas, 4th International School of Nanophotonics and Photovoltaics, Maratea, Italy (2011).

2.2. Cold excitons, 3rd International School on Nanophotonics and Photovoltaics, Zakhadzor, Armenia (2010).

2.1. Cold excitons, 2010 Michigan Summer School "Quantum Simulation and Metrology", Ann Arbor, MI (2010).

3. Talks of Leonid Butov at Universities and Research Labs (since the start of the project in July 2008, these talks are not included to the Number of Papers presented but not Published)

3.13. (seminar) Spontaneous coherence in a cold exciton gas, University of California at Berkeley (Apr 30, 2012).

3.12. (seminar) Spontaneous coherence in a cold exciton gas, University of California at San Diego (Feb 1, 2012).

3.11. (seminar) Indirect excitons: from the physics of cold gases to devices and back, Lawrence Berkeley National Lab (Dec 13, 2011).

3.10. (colloquium) Indirect excitons: from the physics of cold gases to devices and back, Lund University (Nov 18, 2011).

3.9. (seminar) Indirect Excitons, Cardiff University (Dec 8, 2010).

3.8. (seminar) Cold excitons, Cardiff University (Sep 13, 2010).

3.7. (seminar) Indirect Excitons, U.S. Army Research Laboratory, Adelphi, MD (Jul 29, 2010).

3.6. (seminar) Indirect excitons, Stanford University (Feb 1, 2010).

3.5. (seminar) Indirect excitons, MIT, The Center for Excitonics (Apr 22, 2009).

3.4 (seminar) Indirect excitons, University of California at Berkeley (Mar 2, 2009).

3.3. (seminar) Indirect excitons, Nanoscience Center, Los Alamos National Laboratory (Feb 12, 2009).

3.2. (colloquium) Indirect excitons: from the physics of cold gases to devices and back, University of California at Santa Barbara (Jan 30, 2009).

3.1. (colloquium) Indirect excitons: from the physics of cold gases to devices and back, University of California at San Diego (Oct 16, 2008).

4. Oral talks and posters at conferences presented by students of the group (since the start of the project in July 2008)

4.20. (oral talk) Alex High, Jason Leonard, Mikas Remeika, Leonid Butov, Micah Hanson, Art Gossard, Condensation of Excitons in a Trap, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 6 – 11, 2012).

4.19. (oral talk) Alex High, Jason Leonard, Aaron Hammack, Sen Yang, Misha Fogler, Leonid Butov, Tomas Ostatnický, Masha Vladimirova, Alexey Kavokin, Ken Campman, Art Gossard, Spontaneous coherence in a cold exciton gas, Spin currents in a coherent exciton gas, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 6 – 11, 2012).

4.18. (oral talk) J.R. Leonard, M. Remeika, Y.Y. Kuznetsova, A.A. High, L.V. Butov, J. Wilkes, M. Hanson, A.C. Gossard, Transport of Indirect Excitons in a Potential Energy Gradient, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 6 – 11, 2012).

4.17. (oral talk) M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, Excitons in Electrostatic Lattices, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 6 – 11, 2012).

4.16. (oral talk) A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov T. Ostatnický, A.V. Kavokin, A.C. Gossard, Spin Texture in a Cold Exciton Gas, APS March Meeting 2011, Dallas, TX (Mar 21 – 25, 2011).

4.15. (oral talk) J.R. Leonard, A.G. Winbow, M. Remeika, Y.Y. Kuznetsova, A.A. High, A.T. Hammack, L.V. Butov, J. Wilkes, A.A. Guenther, A.L. Ivanov, M. Hanson, A.C. Gossard, Electrostatic conveyer for excitons, APS March Meeting 2011, Dallas, TX (Mar 21 – 25, 2011).

4.14. (oral talk) M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, Excitons in Electrostatic Lattices, APS March Meeting 2011, Dallas, TX (Mar 21 – 25, 2011).

4.13. (oral talk) Y.Y. Kuznetsova, J.R. Leonard, L.V. Butov, J. Wilkes, A.L. Ivanov, A.C. Gossard, Excitation energy dependence of the exciton inner ring, APS March Meeting 2011, Dallas, TX (Mar 21 – 25, 2011).

4.12. (oral talk) Y.Y. Kuznetsova, M. Remeika, A.A. High, A.T. Hammack, L.V. Butov, M. Hanson, A.C. Gossard, All-Optical Excitonic Switch, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 17 – 21, 2010).

4.11. (oral talk) A.G. Winbow, J.R. Leonard, M. Remeika, A.A. High, E. Green, A.T Hammack, L.V. Butov, M. Hanson, A.C. Gossard, Electrostatic Conveyer for Excitons, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 17 – 21, 2010).

4.10. (oral talk) G. Grosso, J.C. Graves, A.T. Hammack, A.A. High, L.V. Butov, M. Hanson, A. Gossard, Excitonic Switches Operating at

Around 100 K, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 17 – 21, 2010).

4.9. (oral talk) A.T. Hammack, L.V. Butov, J. Wilkes, L. Mouchliadis, E.A. Muljarov, A.L. Ivanov, A.C. Gossard, Kinetics of the Exciton Inner Ring Pattern Formation and Thermalization Properties of the Exciton Cloud under One- and Two-Color Pump-Probe Experiments, Quantum Electronics and Laser Science Conference (QELS), San Jose, CA (May 17 – 21, 2010).

4.8. (oral talk) A.G. Winbow, J.R. Leonard, M. Remeika, A.A. High, A.T. Hammack, L.V. Butov, M. Hanson, A.C. Gossard, Electrostatic Conveyers for Excitons, APS March Meeting, Portland, OR (Mar 15 – 19, 2010).

4.7. (oral talk) Aaron Tynes Hammack, Sen Yang, Leonid V. Butov, Arthur C. Gossard, Properties of The Exciton Inner Ring at Ultra-low Temperatures and High Magnetic Fields, The International Quantum Electronics Conference (IQEC), Baltimore, MD (May 31 – Jun 5, 2009).

4.6. (oral talk) A.A. High, A.K. Thomas, G. Grosso, A.T. Hammack, L.V. Butov, A.D. Meyertholen, M.M. Fogler, M. Hanson, A.C. Gossard, A Diamond Trap for Indirect Excitons in Coupled Quantum Wells, The International Quantum Electronics Conference (IQEC), Baltimore, MD (May 31 – Jun 5, 2009).

4.5. (oral talk) J.R. Leonard, Y. Kuznetsova, Sen Yang, L.V. Butov, T. Ostatnick´y, A. Kavokin, A.C. Gossard, Spin transport of indirect excitons in GaAs/AlGaAs coupled quantum wells, The International Quantum Electronics Conference (IQEC), Baltimore, MD (May 31 – Jun 5, 2009).

4.4. (oral talk) M. Remeika, J.C. Graves, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, Localization – Delocalization Transition of Indirect Excitons in Lateral Electrostatic Lattices, APS March Meeting, Pittsburgh, PA (Mar 16–20, 2009).

4.3. (oral talk) Sen Yang, A.T. Hammack, M.M. Fogler, L.V. Butov, L.S. Levitov, B.D. Simons, A.C. Gossard, Spontaneous coherence and kinetics of macroscopically ordered exciton state, 4th International Conference on Spontaneous Coherence in Excitonic Systems, Cambridge, UK (Sep 8–12, 2008).

4.2. (poster) Alex High, Aaron Hammack, Averi Thomas, Ekaterina Novitskaya, Leonid Butov, Leonidas Mouchliadis, Alexei Ivanov, Micah Hanson, Arthur Gossard, Control of Exciton Flux Through Tunable Potential Reliefs, 4th International Conference on Spontaneous Coherence in Excitonic Systems, Cambridge, UK (Sep 8–12, 2008).

4.1. (poster) Aaron Tynes Hammack, Leonid V. Butov, Leonidas Mouchliadis, Alex L. Ivanov, Art C. Gossard, Low temperature behavior of excitons in an optically-induced trap, 4th International Conference on Spontaneous Coherence in Excitonic Systems, Cambridge, UK (Sep 8–12, 2008).

Number of Presentations: 30.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Aaron Hammack	0.49	
Sen Yang	0.49	
Alex High	0.49	
Jason Leonard	0.49	
FTE Equivalent:	**1.96**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Sen Yang
Aaron Hammack
Alex Winbow
Total Number: 3

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

1. We discovered condensation and spontaneous coherence of excitons in a trap [Nano Lett. 12, 2605 (2012)].

2. We discovered patterns of spontaneous coherence, spin textures, and phase singularities in a cold exciton gas [Nature 483, 584 92012)].

3. We developed methods to trap cold excitons [Nano Lett. 9, 2094 (2009); Phys. Rev. Lett. 103, 087403 (2009); Appl. Phys. Lett. 97, 201106 (2010)].

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6. We measured kinetics of the inner ring in the exciton pattern formation and determined exciton transport characteristics [Phys. Rev. B 80, 155331 (2009)].

7. We measured the exciton front propagation in photoexcited GaAs quantum wells by time resolved imaging. These measurements afford a contactless method for probing the electron and hole transport [Phys. Rev. B 81, 115320 (2010)].

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Technology Transfer